Effective Depth of Soil Compaction in Relation to Applied Compactive Energy

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WHRP Project 0092-08-11

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Project Objectives

- To relate degree of soil compaction at various depths as a function of energy applied to the surface, compactor weight, and footprint.
- Development of a monitoring system to evaluate received energy and degree of compaction at various depths
- Determination of the influence of soil parameters (e.g., soil texture, plasticity, and moisture content) on compaction achieved.
- Draft recommendations to optimize lift thickness as function of Wisconsin construction experience and typical compaction equipment and delivered energy.

Compaction of Soils

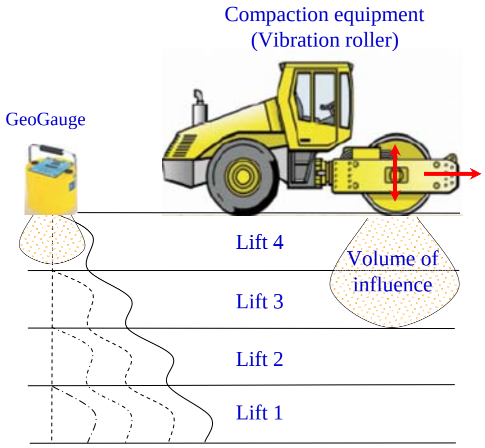
- Several factors influence the compaction (i.e., maximum density or unit weight and optimum water content) of soils:
  - compaction method (i.e., pounding, kneading, pressure, vibration)
  - molding moisture content (soil water content when compacted)
  - compactive effort (applied energy and compactor size)
  - soil type (determines optimum moisture content and max, unit weight)
  - relative layer stiffness (stiff layer over soft layer)

Lift-thickness Specifications

Lift thickness	State DOTs
6-inch	MA, MT, ND
6-inch (compacted)	CT, KY, NY
8-inch	AL, AZ, CA, DE, FL, ID, IL, IN, IA, KS, ME, MN, MS, MO, OR, SC, VT, VA, **WI**
12-inch	LA, NH, NJ, OH, TX

(Hoppe 1999; Lenke 2006)

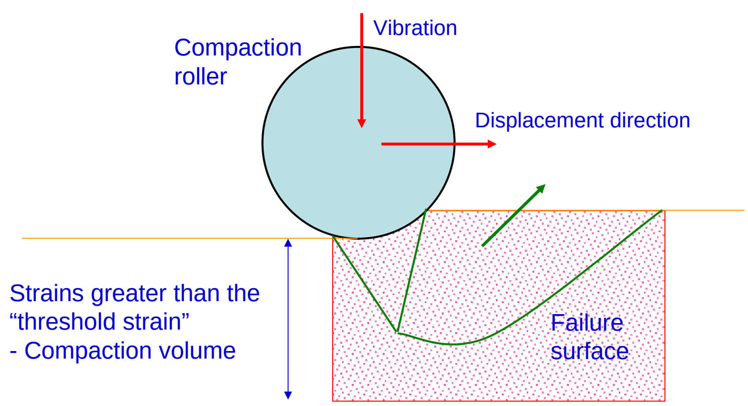
Research Question



Schematic stiffness and density profile versus depth after each lift compaction

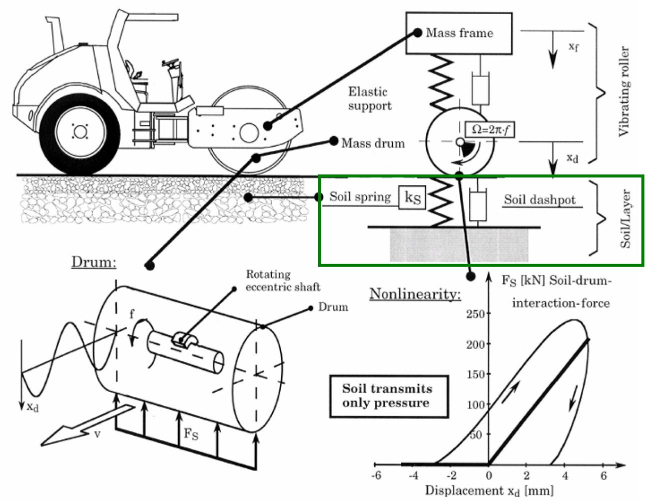
What is the maximum lift thickness that can still provide uniform compaction and proper engineering performance in road embankments?

Field Compaction



Field Compaction

- Energy propagation

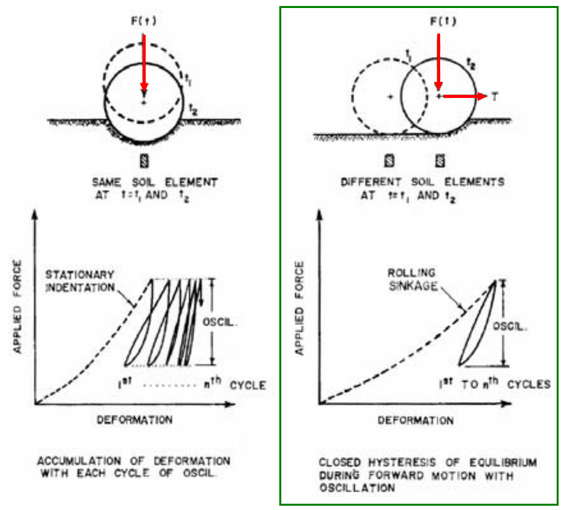


This is our problem

(Anderegg and Kaufmann 2004)

Field Compaction

- Energy propagation



(Yoo and Selig 1979)

Field Site

Testing site: Junction City (15 mi NW of Stevens Points)
Contractor: Hoffmann Construction

To Junction City

Soil Properties

- Basic properties

Soil type	Specific Gravity (Gs)	USCS (Unified Soil Classification System)
Silty soil	2.83	SM
Brown sand	2.66	SP

- Compaction properties

Soil type	maximum dry unit weight (kN/m^3)	optimum water content (%)
Silty soil	18.2	16.7
Brown sand	17.1	9.5

Field Measurements

- Soil property and response measurements:
  - Internal soil deformation: MEMS inclinometers
  - Internal pressure: pressure gauges
  - Density profile: nuclear density gauge and sand cone
  - Surface stiffness: GeoGauge
  - Internal stiffness: P-wave velocity – MEMS accelerometers
  - Volumetric water content: time domain reflectometry (TDR)

Field Measurements

Originally proposed field testing matrix

1 - 6 passes			
Fine-grained Soil		**Coarse-grained Soil**	
Sheepsfoot Roller	**Rubber-tired Roller**	**Smooth-drum Vibratory Roller**	**Rubber-tired Roller**
Dry: 8, 12, 16, and 20" lifts	Dry (4-5%<w_{op}): 8, 12, 16, and 20" lifts	Dry (4-5%<w_{op}): 8, 12, 16, and 20" lifts	Dry (4-5%<w_{op}): 8, 12, 16, and 20 lifts
Wet (4-5%>w_{op}): 8, 12, 16, and 20" lifts	Wet (4-5%>w_{op}): 8, 12, 16, and 20" lifts	Wet (4-5%>w_{op}): 8, 12, 16, and 20" lifts	Wet (4-5%>w_{op}): 8, 12, 16, and 20" lifts

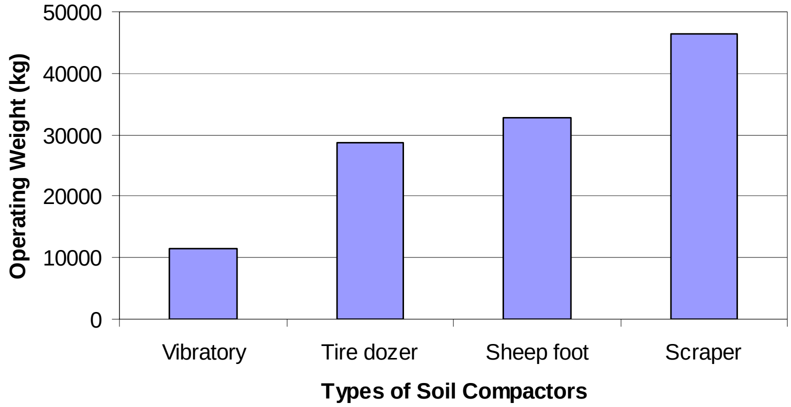
Field Measurements

- Compaction equipment:
  - Caterpillar CS-563E Smooth-drum vibratory roller
  - Caterpillar 824C Rubber-tired roller (dozer)
  - Caterpillar 825C Sheepsfoot roller
  - Caterpillar 631G Scraper
- Two soil types: fine and coarse

Field Compactors

Specifications of Compactors

- Operating weight of compactor is related to the transferred compactive energy



Source: http://www.cat.com

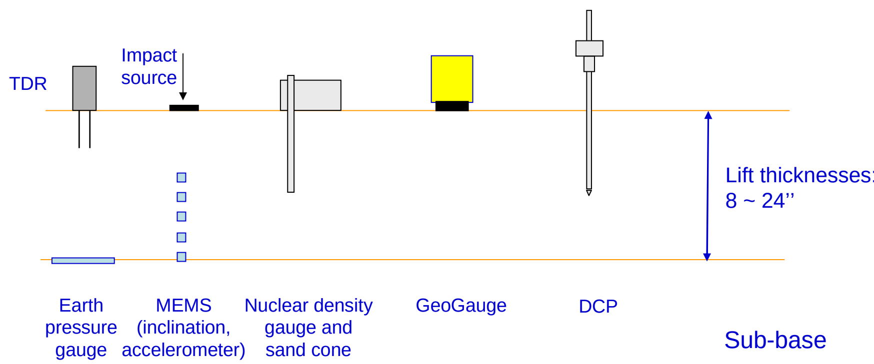
Field Measurements

Actual conducted field testing matrix

Soil type / compactor	Fine grained soil	Nat. moisture sand	Wet sand
Vibratory roller	12, 17, and 24” lifts	8, 13, and 24” lifts	8, 13, and 23” lifts
Rubber-tired roller	8~11, and 20” lifts	8, 13, and 20” lifts	13, and 23” lifts
Scraper	24” lift	13, and 23” lifts	-
Sheepsfoot roller	10~16, and 20” lifts	-	-

Field Measurements

- Field deployment / test section



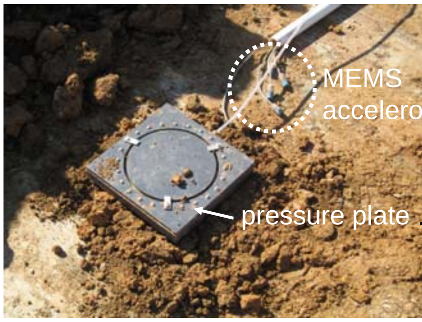
Field Testing: Soil Properties

Field Testing: Energy Compaction

Measurements of changes in internal stresses and accelerations (pressure cell plate and accelerometers)

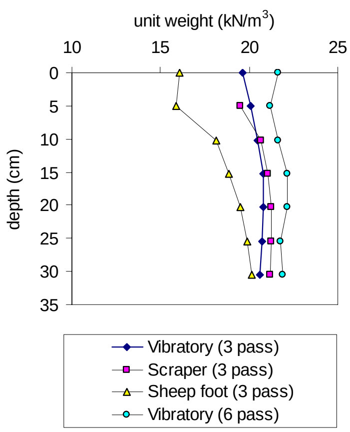
Installation of Sensors

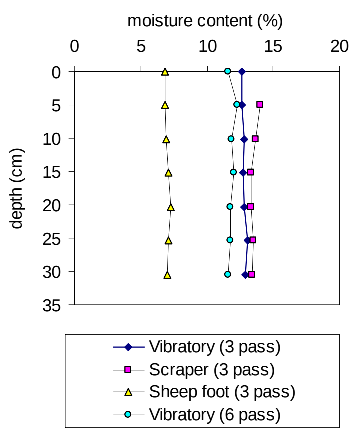
Extraction of Sensors



Effect of Compactor on Dry Unit Weight and Water Content

Nuclear Density Gauge – Fine grained soil



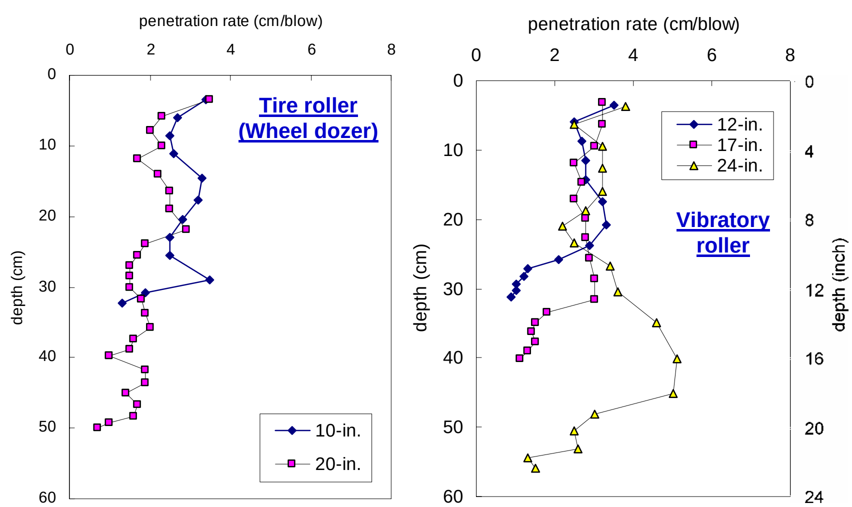


Dynamic Cone Penetrometer

- Dynamic cone penetrometer (DCP): provides an indication of the strength uniformity of soil layers.
- DCP index: is a measure of shear strength as function of dry density and effective stress. That is, the DCP index profiles may give the indication of effect of compaction

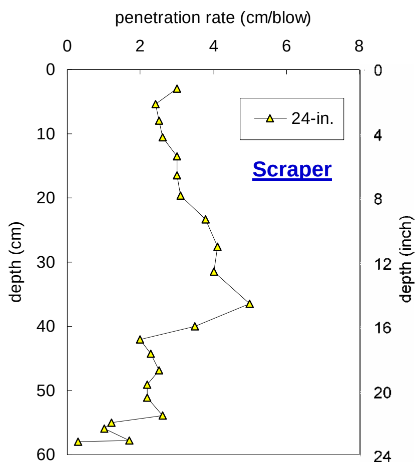
Dynamic Cone Penetrometer

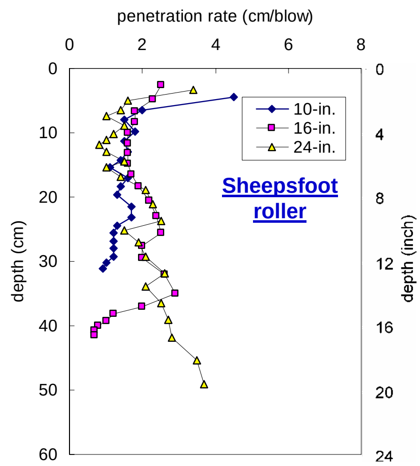
Fine grained soil



Dynamic Cone Penetrometer

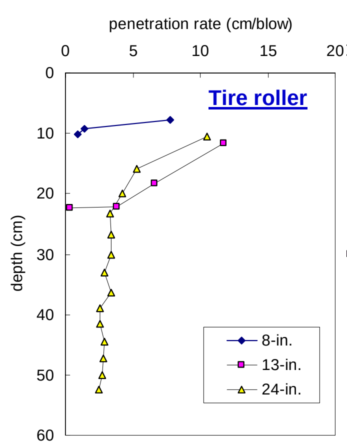
Fine grained soil

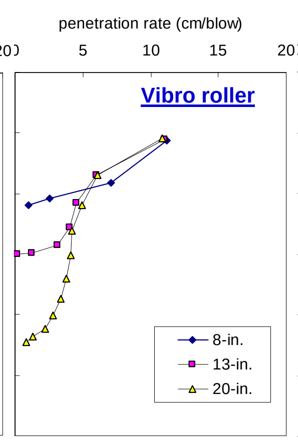


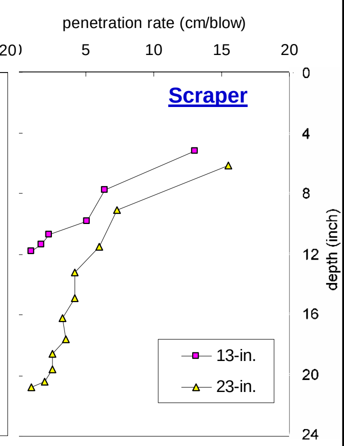


Dynamic Cone Penetrometer

Natural moist sand

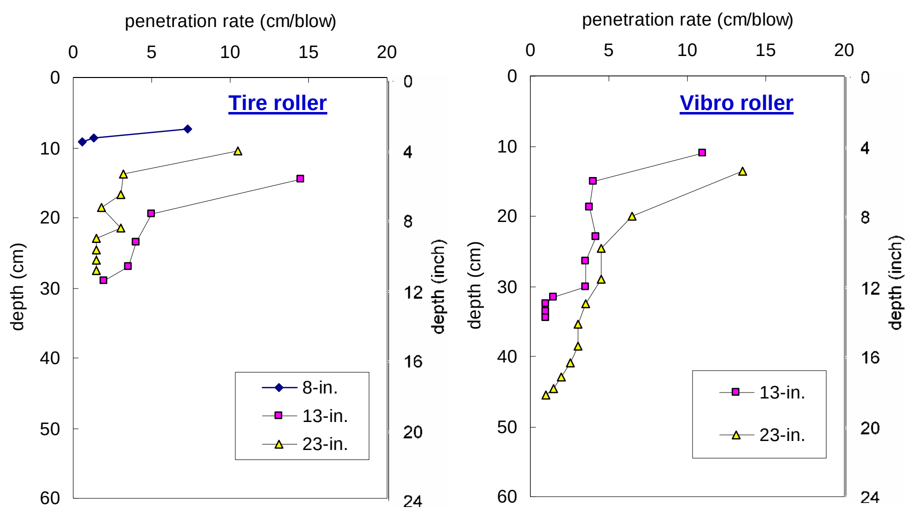






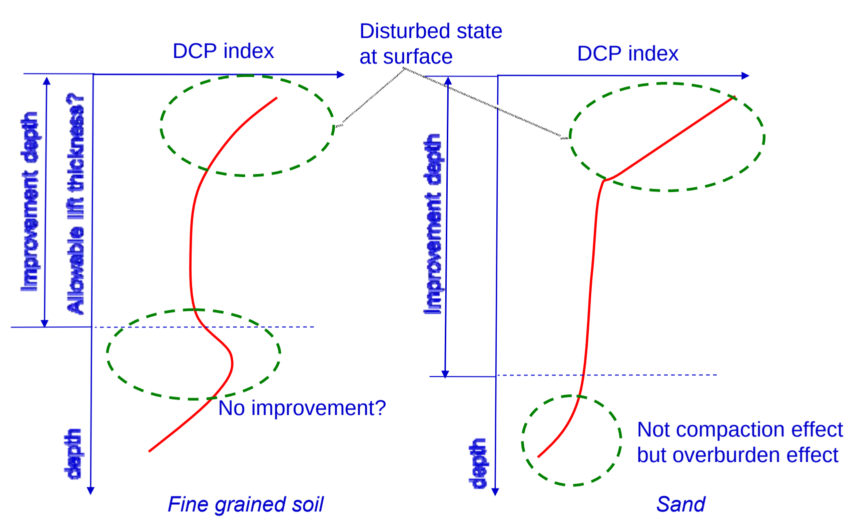
Dynamic Cone Penetrometer

Wet sand



DCP Observations

DCP index and compaction effectiveness

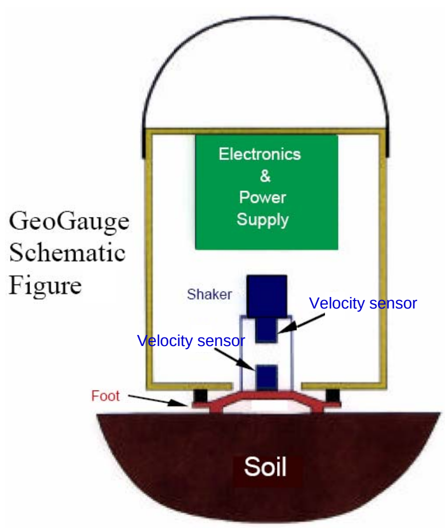


Soil Stiffness Gauge

- SSG
  - SSG measures the impedance at the surface of soil
  - Soil stiffness can be calculated by the impedance

$$K = \frac{P}{\delta} \approx \frac{1.77 \cdot R \cdot E}{1 - \nu^2}$$

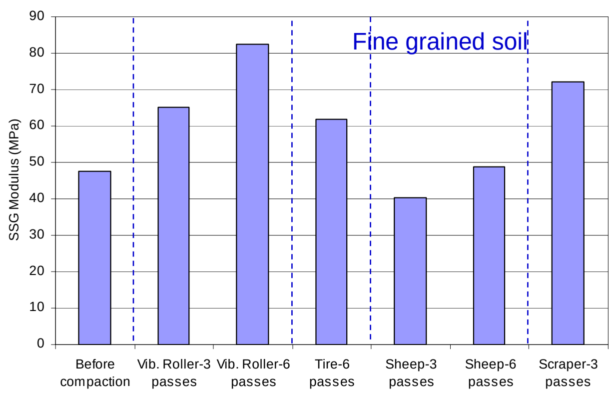
Where,
R: the outer radius of ring foot
E: Young's modulus



http://www.impact-test.com

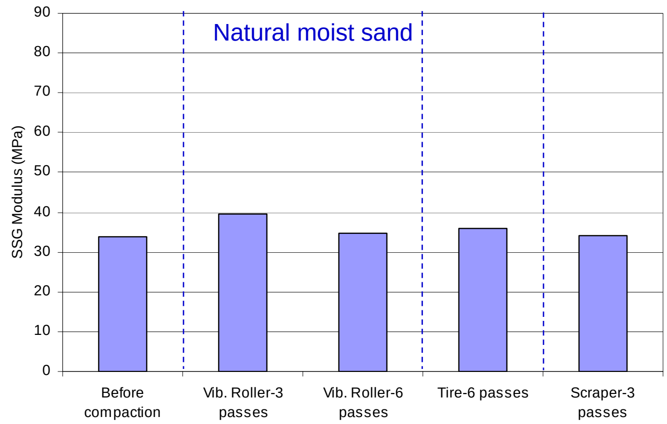
Soil Stiffness Gauge

- The use of different compactors is reflected on modulus.
- Passes also affects stiffness measurements
- Sheep foot compactor does not show improvements (depth limitation of SSG and surface disturbances)



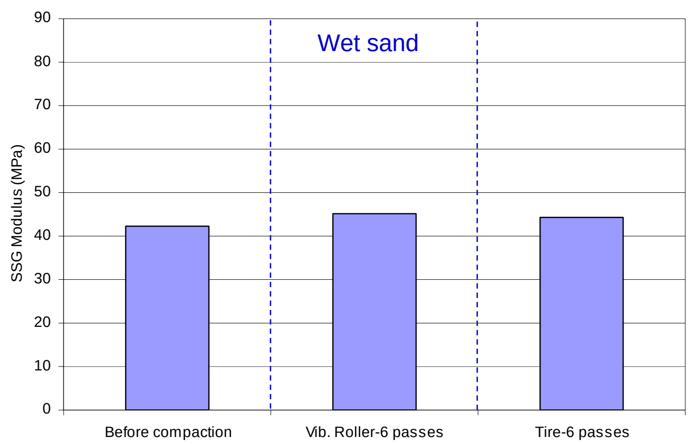
Soil Stiffness Gauge

- Tire roller and scraper on sand created lots of soils displacement.



Soil Stiffness Gauge

- Wet sand stiffness is higher than that of natural moisture sand



Time Domain Reflectometry (TDR)

- TDR
  - Put probe in ground
  - Send electromagnetic pulse
  - Measure travel time of reflected pulse
  - Calculate velocity
  - Determine dielectric permittivity of soil
  - Calculate volumetric water content (Topp et al., 1980)
  - Volumetric water content: $\theta = V_w/V$

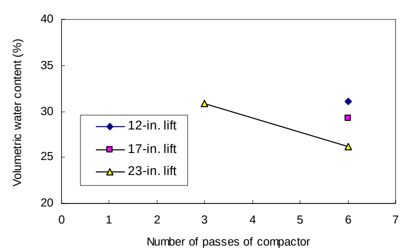
$$\theta = -0.053 + 2.92 \cdot 10^{-2} K_a - 5.5 \cdot 10^{-4} K_a^2 + 4.3 \cdot 10^{-6} K_a^3$$

Source: Fratta 2008

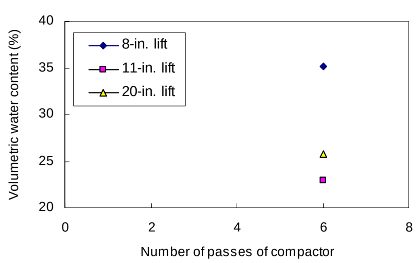
Time Domain Reflectometry

Fine grained soil

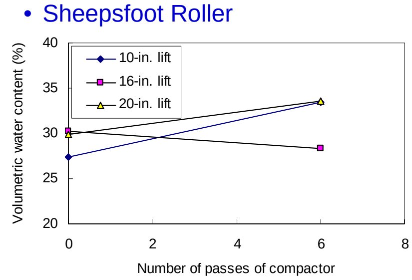
- Vibratory Roller



- Tire Roller (Wheel dozer)



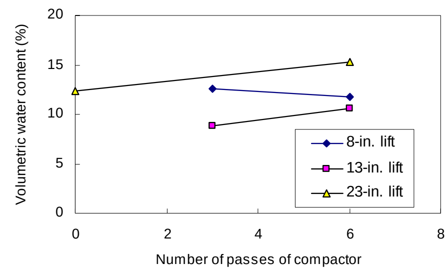
- Sheepsfoot Roller



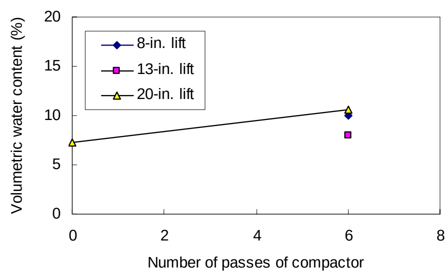
Time Domain Reflectometry

Natural moisture sand

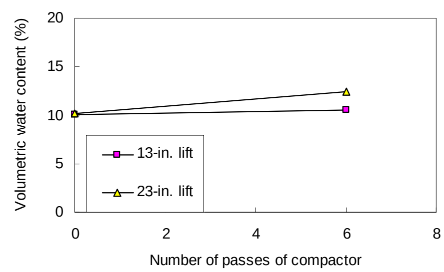
- Vibratory Roller



- Tire Roller (Wheel dozer)



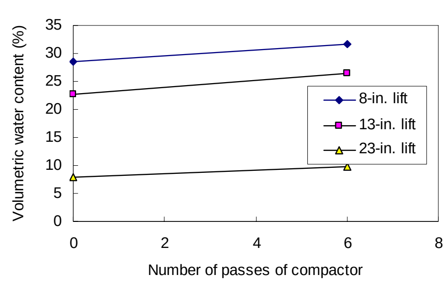
- Scraper



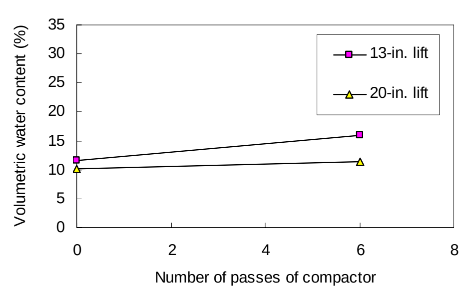
Time Domain Reflectometry

Wet Sand

- Vibratory Roller



- Tire Roller (Wheel dozer)



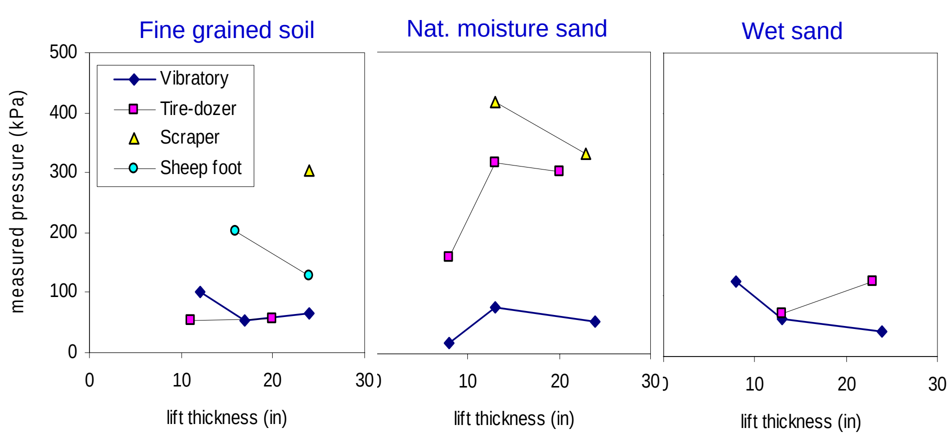
Pressure Cell Plate

- Maximum pressure response was captured for each compactor's passing

Soil Type	Compactor type	Maximum Pressure Response (kPa)		
Fine grained Soil	Vibratory	12" – **101.9**	17" – **53.0**	24" – **64.8**
	Tire-dozer	11" – **52.2**	-	20" – **56.9**
	Scraper	-	-	24" – **304.3**
	Sheep foot	-	16" – **202.9**	24" – **126.7**
Natural moisture sand	Vibratory	8" – **17.2**	13" – **75.7**	24" – **52.0**
	Tire-dozer	8" – **161.1**	13" – **316.5**	20" – **302.4**
	Scraper	-	13" – **417.1**	23" – **330.9**
Wet sand	Vibratory	8" – **122.2**	13" – **61.9**	24" – **42.3**
	Tire-dozer	-	13" – **69.5**	23" – **124.1**

Pressure Cell Plate

- Weight of compaction equipment and lift thickness affect the transferred pressure.

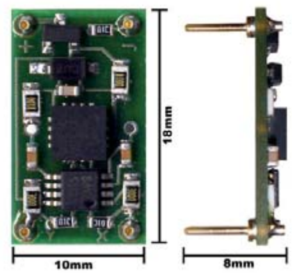


MEMS Measurements

- Direct measurements:
  - Internal soil deformation: MEMS inclinometers

Analog Devices ADLX203 iMEMS accelerometers

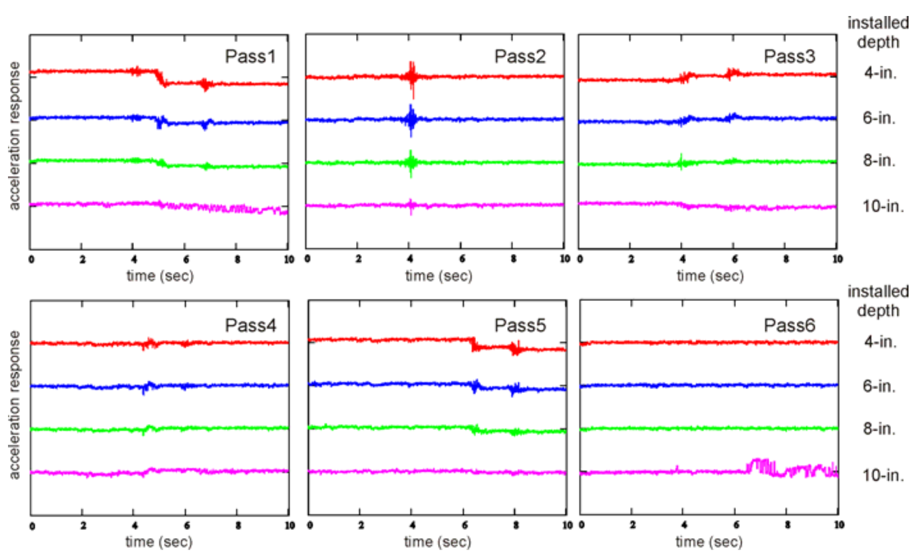
- Low-power consumption; Low-cost
- High sensitivity (750 mV/g)
- Dual axis "Static" Acceleration
  - Gravity: Rotation measurements



Source: http://www.dimensionengineering.com

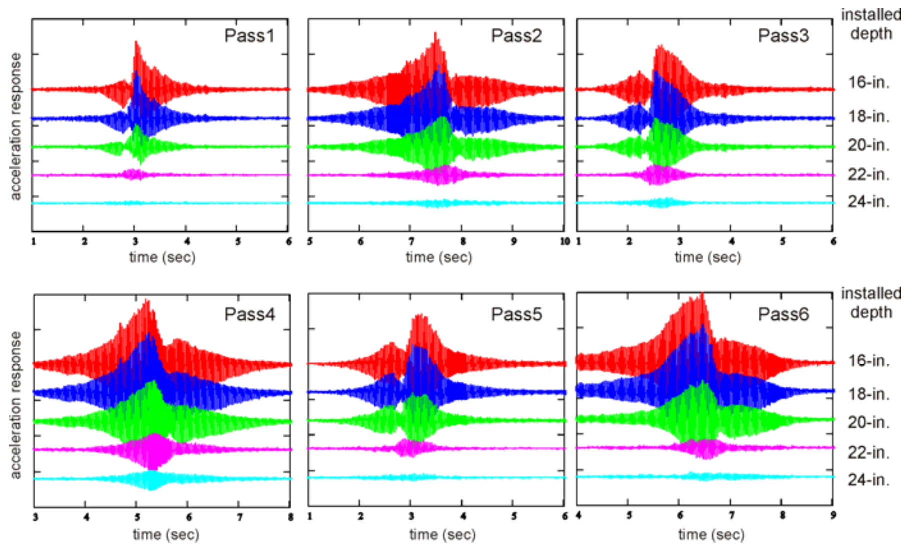
MEMS Measurements

- Fine grained soil, Tire roller, 10-inch lift thickness, Y-axis acc.

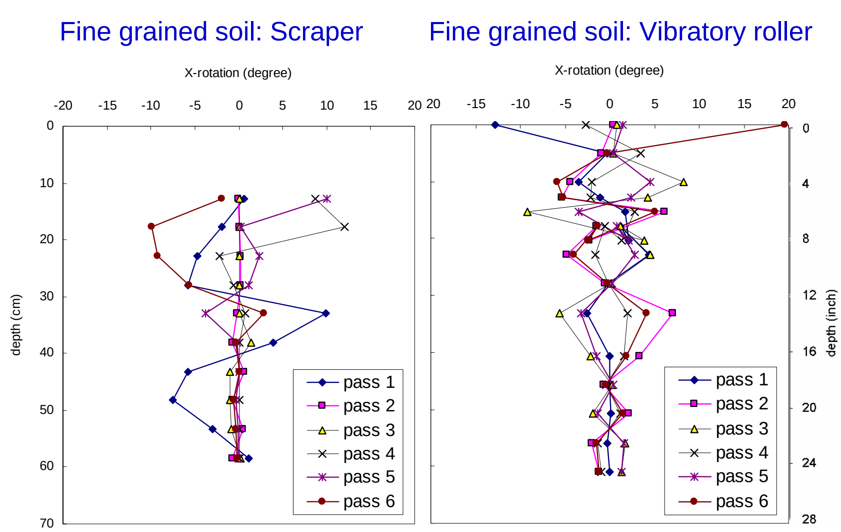


MEMS Measurements

- Fine grained soil, vibratory roller, 24-inch lift thickness, Y-axis acc.

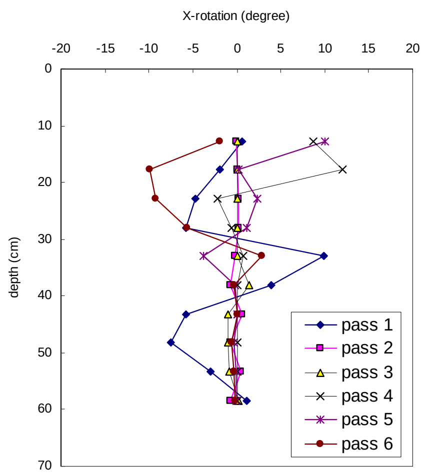


MEMS Measurements

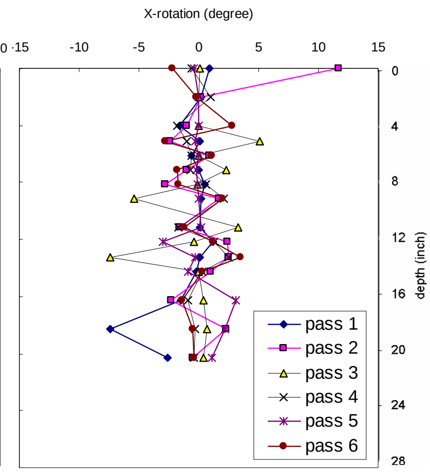


MEMS Measurements

Fine grained soil: Scraper

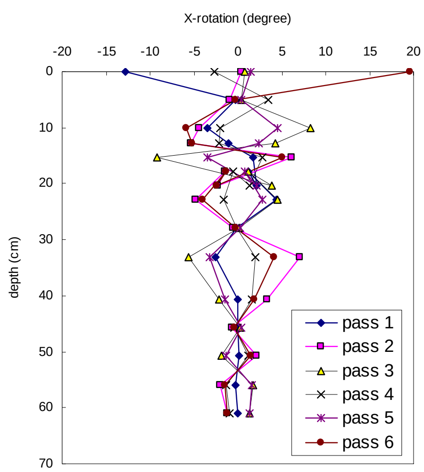


Fine grained soil: Tire roller

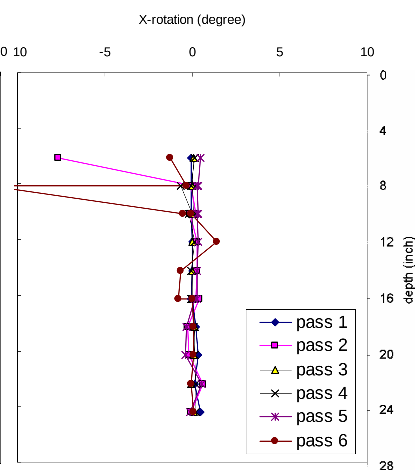


MEMS Measurements

Fine grained soil: Vibratory roller



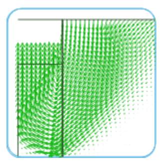
Fine grained soil: Sheepsfoot

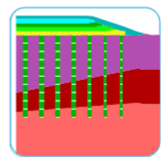


Numerical Simulation

- *FLAC* (Fast Lagrangian Analysis of Continua) is a 2D continuum code for modeling geomaterials and structural behavior.
- The explicit finite difference formulation of the code makes *FLAC* suited for modeling geomechanical problems including static and dynamic

FLAC
Version 5.0





Stress Rotation

- Stress rotation is simulated by FLAC.
- The combination of vertical stress and horizontal stress may affect the induced shear stress -> related to shear distortion which directly affect the compaction.